



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**SALINITY, TEMPERATURE, AND OPTICAL  
CHARACTERIZATION OF A TIDALLY CHOKED  
ESTUARY CONNECTED TO TWO CONTRASTING  
INTRA-COASTAL WATERWAYS**

by

Jeanette Sheets

June 2013

Thesis Advisor:  
Thesis Co-Advisor:

James H. MacMahan  
Edward Thornton

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**SALINITY, TEMPERATURE, AND OPTICAL CHARACTERIZATION OF A  
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INTRA-COASTAL WATERWAYS**

Jeanette Sheets  
Lieutenant Commander, United States Navy  
B.S., Texas A & M University at Galveston, 2003

Submitted in partial fulfillment of the  
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June 2013**

Author: Jeanette Sheets

Approved by: James H. MacMahan  
Thesis Advisor

Edward Thornton  
Thesis Co-Advisor

Peter Chu  
Chair, Department of Oceanography  
Graduate School of School of Engineering and Applied Sciences

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## **ABSTRACT**

Spatial and temporal observations of CDOM, salinity and temperature were obtained in New River Inlet, NC to describe the salinity, temperature and optical characterization of a tidally choked estuary with connecting intra-coastal waterways (ICWs). Four different water masses identified as originating from different regions of the estuary, contribute to the characterization of the inlet: 1) ocean (low CDOM, high salinity, and low temperature water), 2) backbay (high CDOM, lower salinity, and warm temperatures), 3) southern ICW (high CDOM, hyper-saline, warm water), and 4) a mixed region. During flood tides, ocean water is transported into the backbay and during ebb tides, backbay water is transported into the ocean. The proximity of the neighboring inlets affects the exchange processes between the southern and northern ICW. The inlet 36km south of New River causes the southern ICW to respond as a tidally choked channel, reducing exchange processes and resulting in increased CDOM, temperature, and salinity. On the contrary, the inlet 12km north of New River Inlet allows free exchange processes between the ocean and the backbay. An interaction exists between the ICWs and the primary inlet tidal channel, where backbay and ocean water are both transported to the ICWs.

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## TABLE OF CONTENTS

<b>I.</b>	<b>INTRODUCTION.....</b>	<b>1</b>
<b>II.</b>	<b>FIELD SITE AND OBSERVATIONS.....</b>	<b>3</b>
	<b>A. CAST OBSERVATIONS.....</b>	<b>4</b>
	<b>B. MINI CATAMARAN OBSERVATIONS .....</b>	<b>6</b>
<b>III.</b>	<b>RESULTS .....</b>	<b>9</b>
	<b>A. CASTS.....</b>	<b>9</b>
	<b>B. MINI CATAMARANS-MAIN CHANNEL AND SIDE BAYS.....</b>	<b>12</b>
	<b>C. MINI CATAMARANS-ICWN .....</b>	<b>16</b>
	<b>D. MINI CATAMARANS-ICWS.....</b>	<b>16</b>
<b>IV.</b>	<b>DISCUSSION .....</b>	<b>21</b>
	<b>A. WATER MASS IDENTIFICATION .....</b>	<b>21</b>
	<b>B. WATER CIRCULATION.....</b>	<b>21</b>
	<b>LIST OF REFERENCES.....</b>	<b>25</b>
	<b>INITIAL DISTRIBUTION LIST .....</b>	<b>27</b>

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## LIST OF FIGURES

Figure 1.	Google Earth Image of New River Inlet, NC. The main regions of the inlet system are outlined: main channel, backbay and the ICW north and south. The colored dots indicate the positions of the casts. The yellow semicircle represents the ebb delta. Colors denote depth averaged salinity in psu, higher and lower values are represented by warmer and cooler colors, respectively. ....	3
Figure 2.	Demeaned <b>a)</b> Ocean and <b>b)</b> backbay sea surface fluctuation versus time overlaid on mini catamaran (shaded columns A-E) and cast (dotted lines) collection time frames. ....	4
Figure 3.	Representative vertical profiles for each region: red=ICWS, green=ICWN, blue=MC, magenta=BackBay, cyan=ebb delta. The profile from the ebb delta is the only one to show stratification. ....	5
Figure 4.	A Google Earth image showing the spatial distribution of the mini catamarans, the colors represent the yearday: yd121=green, yd124=yellow, yd125=blue, yd127=orange and yd131=red. The number is the catamaran identifier, C1–C6. ....	6
Figure 5.	Depth averaged spatial plots of all casts for <b>a)</b> CDOM, <b>b)</b> salinity and <b>c)</b> temperature. Warm colors represent higher CDOM, salinity and temperature. The box inset is expanded on the right. ....	10
Figure 6.	Comparison of cast data in <b>a)</b> TS-CDOM versus <b>b)</b> TS diagrams. The markers in Figure10a represent the different regions: Squares=ICWS, Triangles=ICWN, Stars=From the open ocean to the ICW intersection and Circles=From the ICW intersection to the backbay. The circled regions represent the water masses: solid=ICWS, dotted=BackBay, and dashed=ebb delta. ....	11
Figure 7.	<b>a)</b> Salinity, <b>b)</b> temperature, <b>c)</b> streamwise velocity, and <b>d)</b> demeaned pressure of mini catamaran data from the backbay (gold line) to the inlet entrance (blue line). The colored lines represent the catamaran identifier from Figure 3: C1=blue, C2=green, C3=red, C4=cyan, C5=magenta, C6=gold. ....	14
Figure 8.	Minicat data from side bays, from left to right are stations C1, C2, and C3. ...	15
Figure 9.	Mini catamaran data from the main channel (yd121) and the ICWN (yd125 and 131), <b>a)</b> salinity, <b>b)</b> temperature, <b>c)</b> streamwise velocity, and <b>d)</b> demeaned pressure. Yeardays 125, and 131 have a common y-axis. For each yearday, the color represents the catamaran identifier from Figure 3: C4=cyan, C5=magenta, C6=gold. ....	18
Figure 10.	Mini catamaran data from the ICWS, <b>a)</b> salinity, <b>b)</b> temperature, <b>c)</b> streamwise velocity, and <b>d)</b> demeaned pressure. For each yearday, the color represents the catamaran identifier from Figure 3: C1=blue, C2=green, C3=red. ....	19

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# **I. INTRODUCTION**

Estuarine water circulation is traditionally assessed using acoustic doppler current profilers (ADCPs), salinity, and temperature. Other methods include drifters, dye release, and modeling. ADCPs are expensive, and dye release and drifters require many runs to fully capture the circulation of an estuary. Though modeling does not require fieldwork, its accuracy increases when combined with in-situ observations. While dye, drifters, and ADCPs provide current velocity, they do not discriminate between physically or biogeochemically different coherent bodies of water, i.e., water masses. As a result, ADCPs are used in conjunction with salinity and temperature measurements to provide an overall picture of water circulation and water mass movement.

In addition to temperature and salinity, a third tracer can contribute a more in-depth understanding of water mass movement. The large optical property gradient between coastal and ocean waters has been used to trace the extent of coastal water influence in the ocean and to track river plumes in open water (Chen 1999). In one particular case, the addition of chlorophyll a fluorescence performed better than salinity and temperature alone in distinguishing fine-scale, ocean structures in satellite imagery (Palacios et al. 2012). By including water's optical properties in the study of estuary circulation, a more detailed account of water mass circulation can be observed.

The optical properties of water, the wavelengths at which it absorbs and fluoresces, are a function of turbidity and biological content, such as the quantity of phytoplankton or dissolved organic material (DOM) (Smart 2004). An important fraction of DOM is chromophoric, or color dissolved, organic matter (CDOM) (Chen 1999) that consists of the humic and fluvic acids (yellow substance) of decaying plant matter (Nieke et al. 1997). Like chlorophyll, CDOM is a major light-absorbing constituent in water. CDOM absorption is strongest in the ultraviolet to blue spectrum and decreases exponentially with increasing wavelength (Stedmon 2000). CDOM affects the quality and quantity of light that reaches photosynthetic cells, thereby controlling phytoplankton production, and hence chlorophyll a concentration. As a result, light absorption in coastal waters is dominated by CDOM, while light absorption in ocean waters is dominated by

phytoplankton (Nieke 1997). CDOM has also been found to be semi conservative in coastal waters, (Hojerslev 1988) it is therefore a better optical tracer than chlorophyll.

Water masses, their movement and overall water circulation are examined at New River Inlet, NC, its estuary and intersecting Intracoastal Waterway (ICW), using CDOM, salinity, temperature and velocity observations acquired from 29 April–21 May 2012. This study describes the effect of neighboring inlet proximity on water exchange processes at New River Inlet, as well as the interaction between the ICWs and the primary inlet tidal channel.



## II. FIELD SITE AND OBSERVATIONS

The following geomorphic features affect the circulation of this system. The New River empties into the Atlantic Ocean between two barrier islands, forming an ebb tidal delta approximately one kilometer in radius (Figure 1). Before reaching the Atlantic, the river opens up into an estuary, through which the main channel (MC) connects the ocean to a large surface area backbay. The Atlantic Intracoastal Waterway (ICW), which extends from Florida to Virginia, intersects the river between the coast and the barrier islands. This paper divides the ICW into north (ICWN) and south (ICWS) of New River (Figure 1). The main channel and the ICWS have multiple side bays including Chadwick Bay, the first major bay south of the ICW/New River intersection.

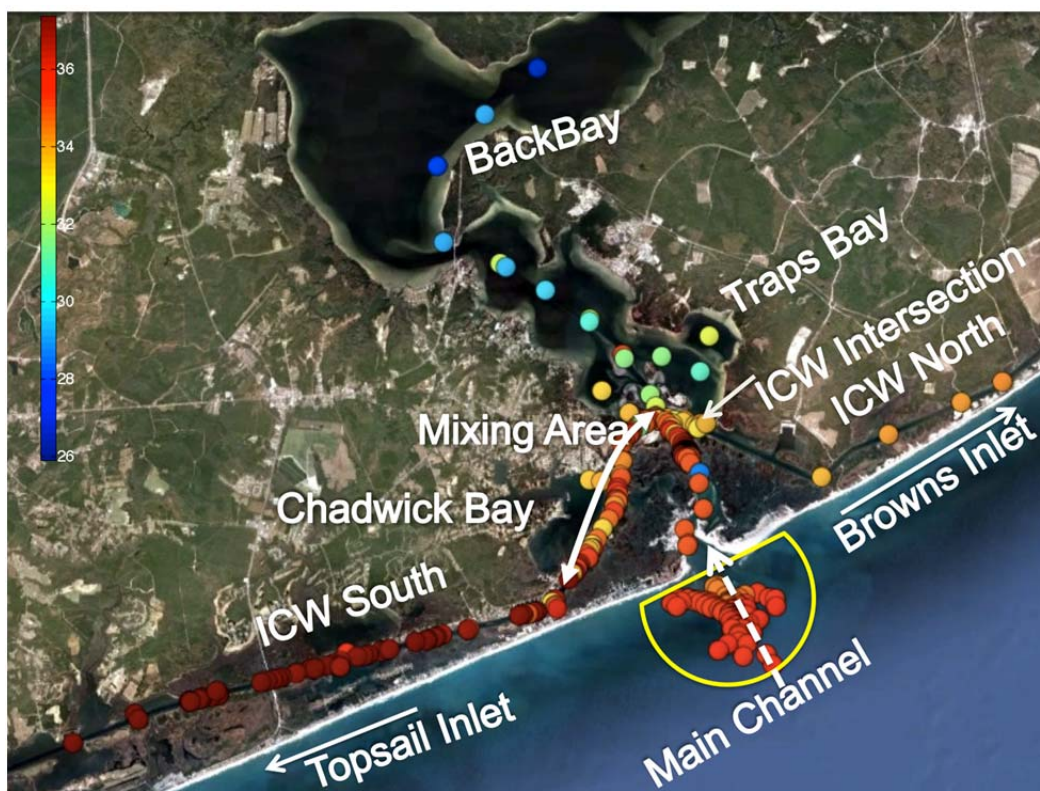


Figure 1. Google Earth Image of New River Inlet, NC. The main regions of the inlet system are outlined: main channel, backbay and the ICW north and south. The colored dots indicate the positions of the casts. The yellow semicircle represents the ebb delta. Colors denote depth averaged salinity in psu, higher and lower values are represented by warmer and cooler colors, respectively.

The tide at New River Inlet is primarily semidiurnal (Figure 2a). The inlet acts like a low-pass filter causing the estuary to be tidally choked such that the tidal amplitude in the backbay is significantly decreased (Figure 2b). Two other inlets interconnect the ICW; 36 km south of New River is New Topsail Inlet, and 12 km to the north is Browns Inlet. The proximity of New Topsail Inlet causes the ICWS to be tidally choked compared to the ICWN. Additionally, both the ICW and main channel are routinely dredged for shipping. The spoils are deposited along the main channel, thereby increasing the length of the tidal channel and aiding in the formation of tidal intrusion fronts in the backbay.

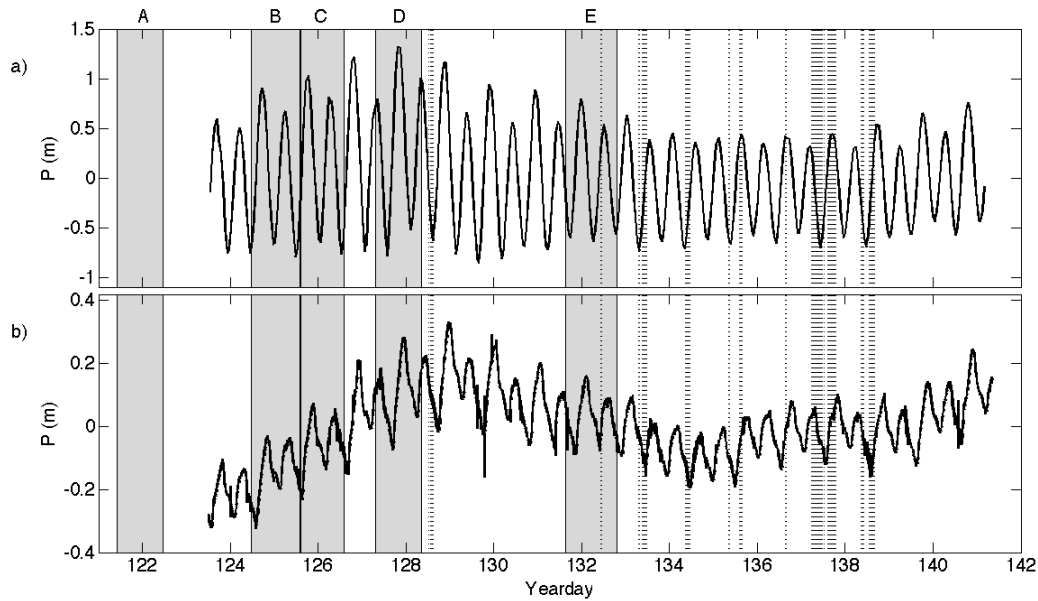


Figure 2. Demeaned **a)** Ocean and **b)** backbay sea surface fluctuation versus time overlaid on mini catamaran (shaded columns A-E) and cast (dotted lines) collection time frames.

## A. CAST OBSERVATIONS

Optical and CTD casts were acquired from 11–17 May 2012. CDOM, chlorophyll, and turbidity were sampled at 3Hz using a single WetLabs ECO-3 optical sensor. The RBR XR-620 logger sampled conductivity, temperature and depth (CTD) at 6 Hz. The sensors were mounted vertically and oriented downward, 1–2 inches off the bottom of a protective cage, which was hand-cast off a small boat. A total of 284 casts

were spatiotemporally and tidally distributed throughout the ICWS, the backbay, ICWN and the main channel (Figure 1). Additionally, 84 CTD-only casts were acquired in the ebb delta primarily during ebb tide. The cast data include one 13-hour sampling event across the main channel to evaluate CDOM concentrations over the length of a tidal cycle. All data were subsampled to 3Hz within the inlet and 2 Hz outside the inlet for analysis.

The vertical variability of salinity was negligible in all regions except the ebb delta (Figure 3). Since this variability was consistent across CDOM, temperature and salinity, all profiles were depth averaged. A spike in turbidity indicated that the cage disturbed bottom sediments, thus the bottom-most 0.05m of data were excluded. Due to stratification at the ebb delta, casts collected at this location were averaged only over the first meter.

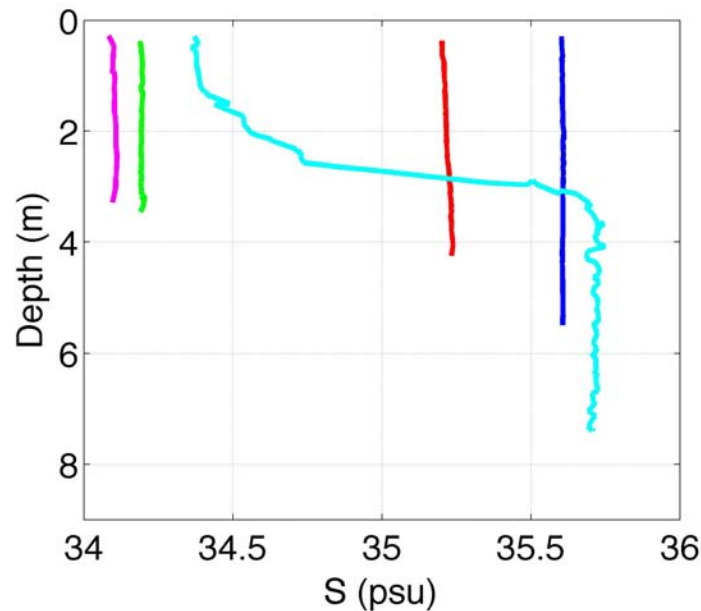


Figure 3. Representative vertical profiles for each region: red=ICWS, green=ICWN, blue=MC, magenta=BackBay, cyan=ebb delta. The profile from the ebb delta is the only one to show stratification.

## B. MINI CATAMARAN OBSERVATIONS

In addition to casts, continuous observations of temperature and salinity were conducted using six mini-catamarans (minicats) on yeardays (yd) 121, 125, 126, 128, and 132. To allow for tidal harmonic analysis, each minicat equipped with a suite of instruments was anchored to the seabed for a period greater than 24 hours. Sea surface elevation (demeaned hydrostatic pressure head) was sampled at 1 Hz using a pressure sensor attached to the minicat anchor. A CTD (sampling rate of 1 Hz) and a downward facing ADCP were attached to the minicat near the surface. The ADCP measured velocity in 50 cm bins, which was averaged over 10 min intervals. The six minicats were spatiotemporally distributed across the study site (Figure 4). To aid in tidal analysis, long-term (~3 weeks) pressure measurements were observed in the ocean outside the ebb delta and in the backbay.



Figure 4. A Google Earth image showing the spatial distribution of the mini catamarans, the colors represent the yearday: yd121=green, yd124=yellow, yd125=blue, yd127=orange and yd131=red. The number is the catamaran identifier, C1–C6.

Minicat CTD data were cleaned and then low-pass filtered. The ADCP's magnetic earth coordinate system was rotated to align with streamwise flow, with positive velocity either southerly or inland. Due to the limitations of minicat deployments, water circulation was analyzed from data composited across different yeardays and was conducted under the assumption that the semidiurnal nature of the inlet does not produce large inter-daily fluctuations of salinity, temperature, and velocity.

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### III. RESULTS

#### A. CASTS

The spatial overview of casts (Figure 5) shows two regions in New River Inlet that are high in CDOM (~26ppb), the backbay and the ICWS. Salinity however, does not reflect a similar distribution. The backbay is brackish (~25psu), while the ICWS, when compared to the 35.5psu of ocean water, is hyper-saline, ~37psu. The temperature distribution also highlights the differences between the backbay and the ICWS, with the latter approximately 1°C warmer. The mixing area (see Figure 1) of the ICWS exhibits high variability in salinity, temperature, and CDOM. Additionally, while salinity and temperature remain consistent from the ebb delta past the ICW intersection, there is an increasing temperature and CDOM gradient and a decreasing salinity gradient from the ICW split to the backbay.

A temperature–salinity-CDOM diagram clearly highlights the three different water masses and a mixed water mass (Figure 6). The ICWS water mass (black circle) consists of warm, hyper-saline, CDOM rich (25°C, 37psu, 25ppb) water. The second water mass (dashed circle) consists of cold, saline and low CDOM ocean water (22.4°C, 35.5psu, 7ppb), found at the entrance of the inlet and in the ICWS, in the vicinity of Chadwick Bay. The third water mass has decreasing CDOM and temperature gradients with an increasing salinity gradient (dotted circle). The mixed water mass (no circle) has intermediate temperature salinity and CDOM (22.5–23.5°C, 32.5–35psu, 9–16 ppb) and is found in the ICWN, the ICW split and the mixing area of the ICWS.



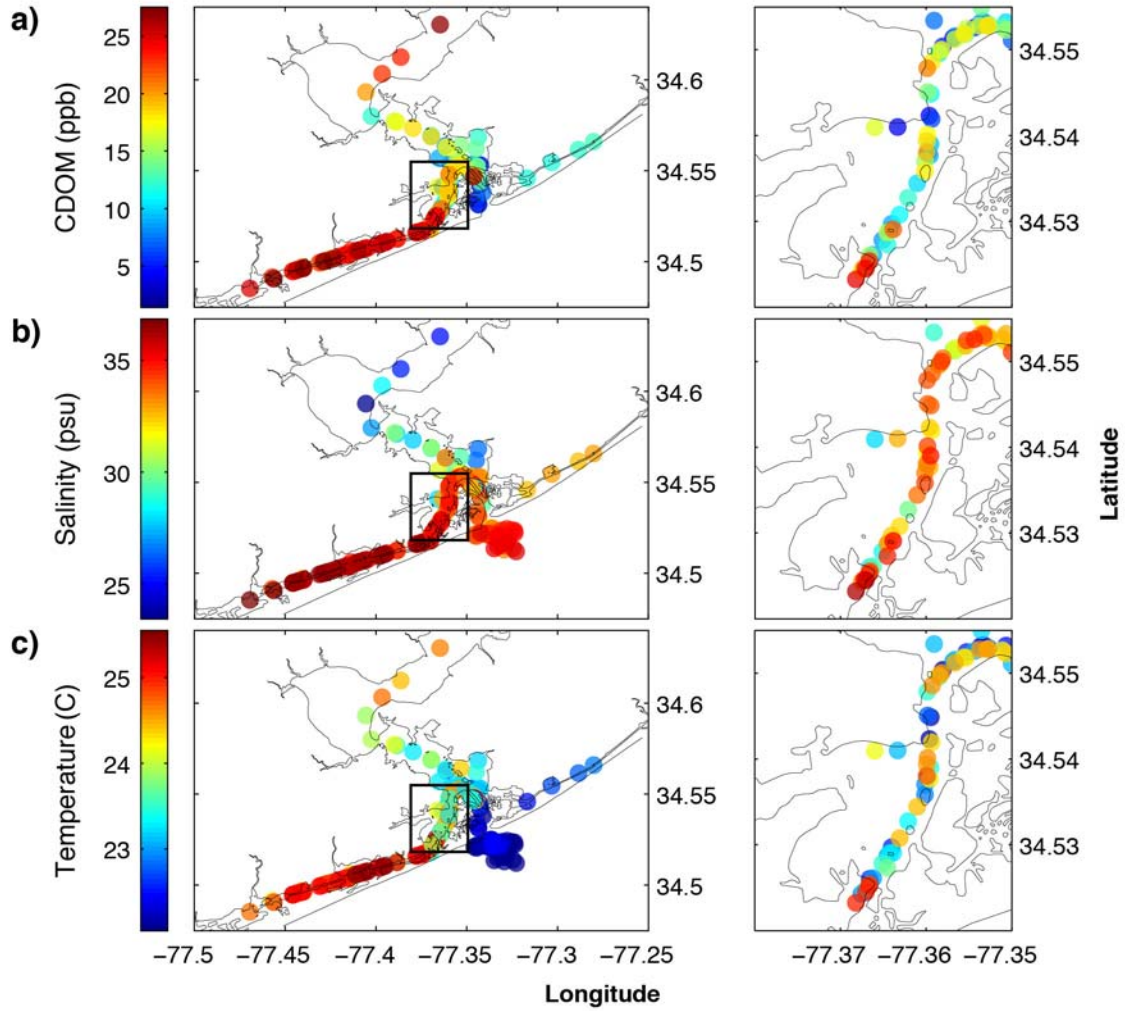


Figure 5. Depth averaged spatial plots of all casts for **a)** CDOM, **b)** salinity and **c)** temperature. Warm colors represent higher CDOM, salinity and temperature. The box inset is expanded on the right.



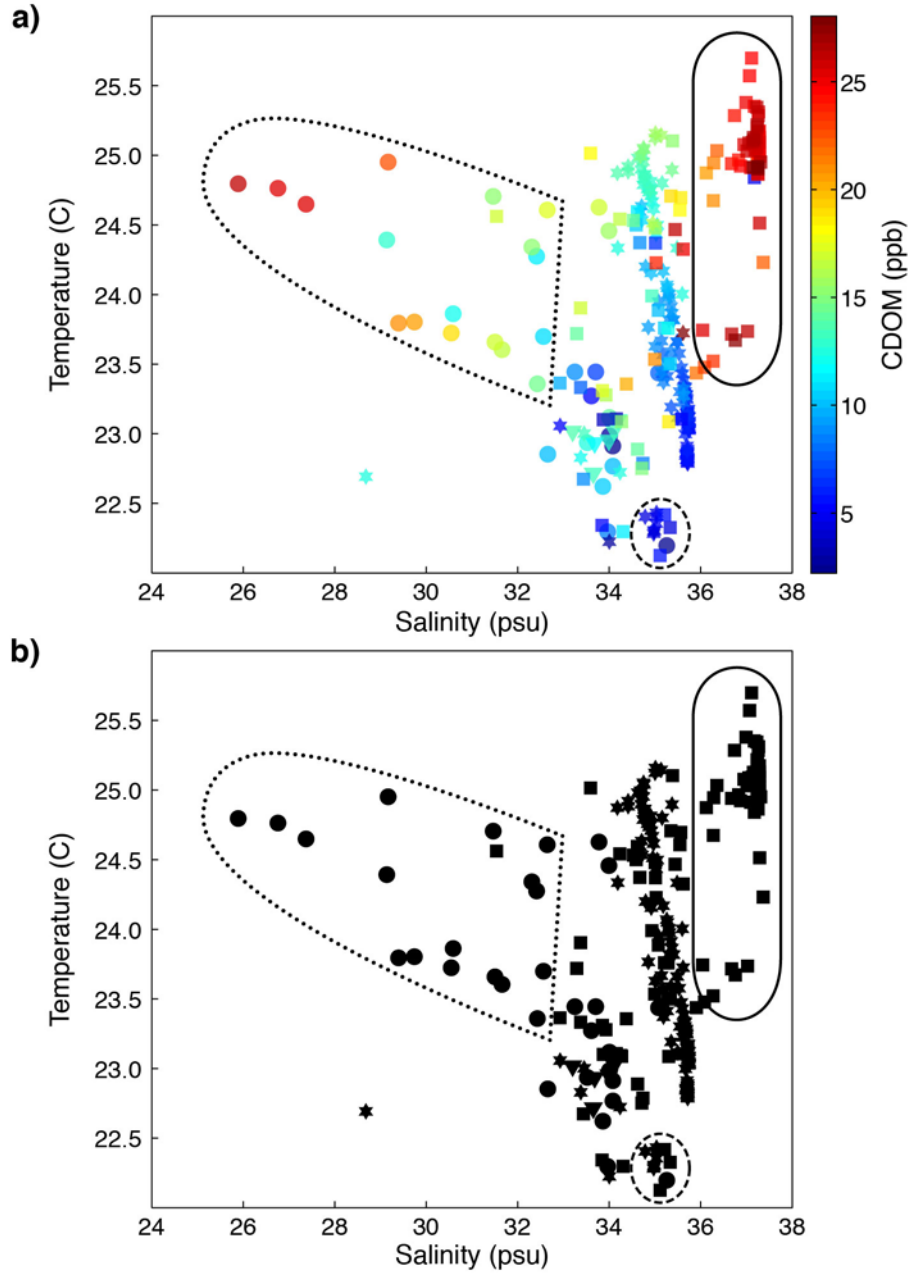


Figure 6. Comparison of cast data in **a)** TS-CDOM versus **b)** TS diagrams. The markers in Figure 10a represent the different regions: Squares=ICWS, Triangles=ICWN, Stars=From the open ocean to the ICW intersection and Circles=From the ICW intersection to the backbay. The circled regions represent the water masses: solid=ICWS, dotted=BackBay, and dashed=ebb delta.

## **B. MINI CATAMARANS-MAIN CHANNEL AND SIDE BAYS**

The main channel is examined using minicats that spread from the inlet entrance to the backbay on yd121, and from the bend in the main channel to the middle of the backbay on yd124. Tidal variability differs with location, but primarily ranges from  $\pm 0.4\text{m}$  at the inlet entrance, decreasing to  $\pm 0.06\text{m}$  in the backbay. Salinity and temperature vary with the tidal cycle and location, but in general they range from 27.5–35.5psu and from 20.3–25°C. For each yearday, the pressure head timeseries shows a wave that decreases in amplitude from the inlet entrance to the backbay (Figure 7d). In the main channel, streamwise velocity and pressure head are in-phase; the flood tide is associated with positive (inland) velocity. The velocity difference between the inlet and the backbay is low,  $\sim 0.2\text{ m/s}$ , with the greatest velocity flux occurring before ( $\pm 1\text{m/s}$  at C4 yd124) and after ( $\pm 0.5\text{ m/s}$  at C4 yd121) the ICW intersection. Unlike pressure head and velocity, temperature and salinity fluctuations are not in-phase within the main channel.

During an incoming tide (yd121), salinity increases, reaching a maximum of 35.5psu at peak flood (C4–C6). This maximum arrives 2.25 hours later at C3 as 35psu and never reaches C1. The salinity maximum plateaus for the duration of the flood and through the initial stages of the ebb; the plateau at C3 however, is much shorter in duration. During ebb tide, salinity decreases as expected, but with variability. The sharpest change ( $\sim 2\text{psu}$ ) occurs during slack water at stations C1 and C3. Although a similar dip is found at station C4, it is not as severe ( $< 0.5\text{psu}$ ) and it occurs before the turn of the tide. In each of these stations, the salinity increases slightly after the dip and continues with the variability and a downward trend. The salinity at station C4 however, plateaus for a short period before continuing to decrease. The amplitude of all variability decreases toward the inlet opening and is not present during flood tide. At each location, the salinity maximum is timed in conjunction with a temperature minimum, the coldest of which is 20.3°C. As the flood tide begins to weaken, temperature increases at all locations, with maximums found at the turn of the tide at stations C1 and C3. At the height of ebb tide, temperatures from C1–C6 plateau at 22.4°C, decreasing once again as

the tide turns. The general flux pattern of salinity, temperature, and velocity, in relation to pressure head, is similar between yd121 and yd124.

Minicats from yearday 124 are centered on the ICW intersection and cover a shorter length than yd121. The closer spacing of minicats results in smaller amplitude separations, i.e., temperature and salinity amplitudes separation is greater on yd121 when minicats were spaced farther apart. Utilizing that difference, yd124 highlights the ebb-salinity variability described on yd121. The largest salinity changes of ~2psu occur at C1 and C2 and decrease to a minimum of <0.5psu at stations C3–C6. The ebb-temperature variability is also highlighted by yd124 with a flux of up to 2°C found at stations C1–C3. The variability reduces to a minimum (<0.5°C) from stations C4–C6. With the exception of C4, stations C3–C6 exhibit variability only through the max ebb. Station C4 continues to show variability until the tide turns.

The side bays were examined using minicats from yd127 (Figure 8). Minicat C1 was positioned in the bay south of the dredge spoils; C2 was located in Traps Bay and C3 between the spoils and Traps Bay. Similar to the main channel, station C1 has velocity and pressure head in phase. Salinity maximum plateaus at 35.5psu and temperature reaches a minimum of 21°C, both occur during maximum pressure and velocity. Station C3 shows velocity and pressure head in phase, however, salinity and temperature fluctuate, reaching a peak salinity of 35.5psu and a temperature low of 22°C. Station C2 is the most different, although pressure head matches station C3, there is little variability in velocity, temperature or salinity, which ranges between 33 and 34psu.

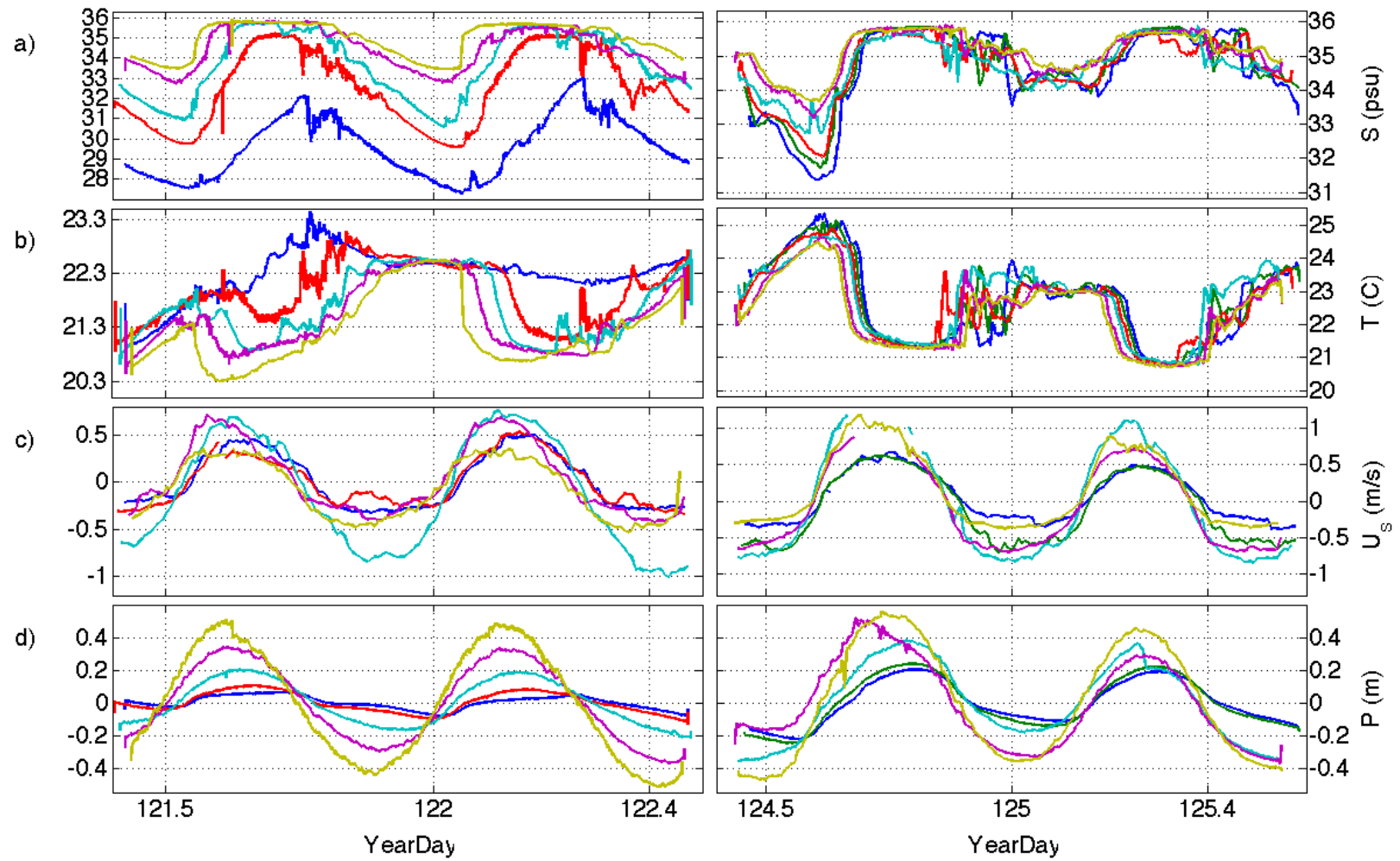


Figure 7. **a)** Salinity, **b)** temperature, **c)** streamwise velocity, and **d)** demeaned pressure of mini catamaran data from the backbay (gold line) to the inlet entrance (blue line). The colored lines represent the catamaran identifier from Figure 3: C1=blue, C2=green, C3=red, C4=cyan, C5=magenta, C6=gold.

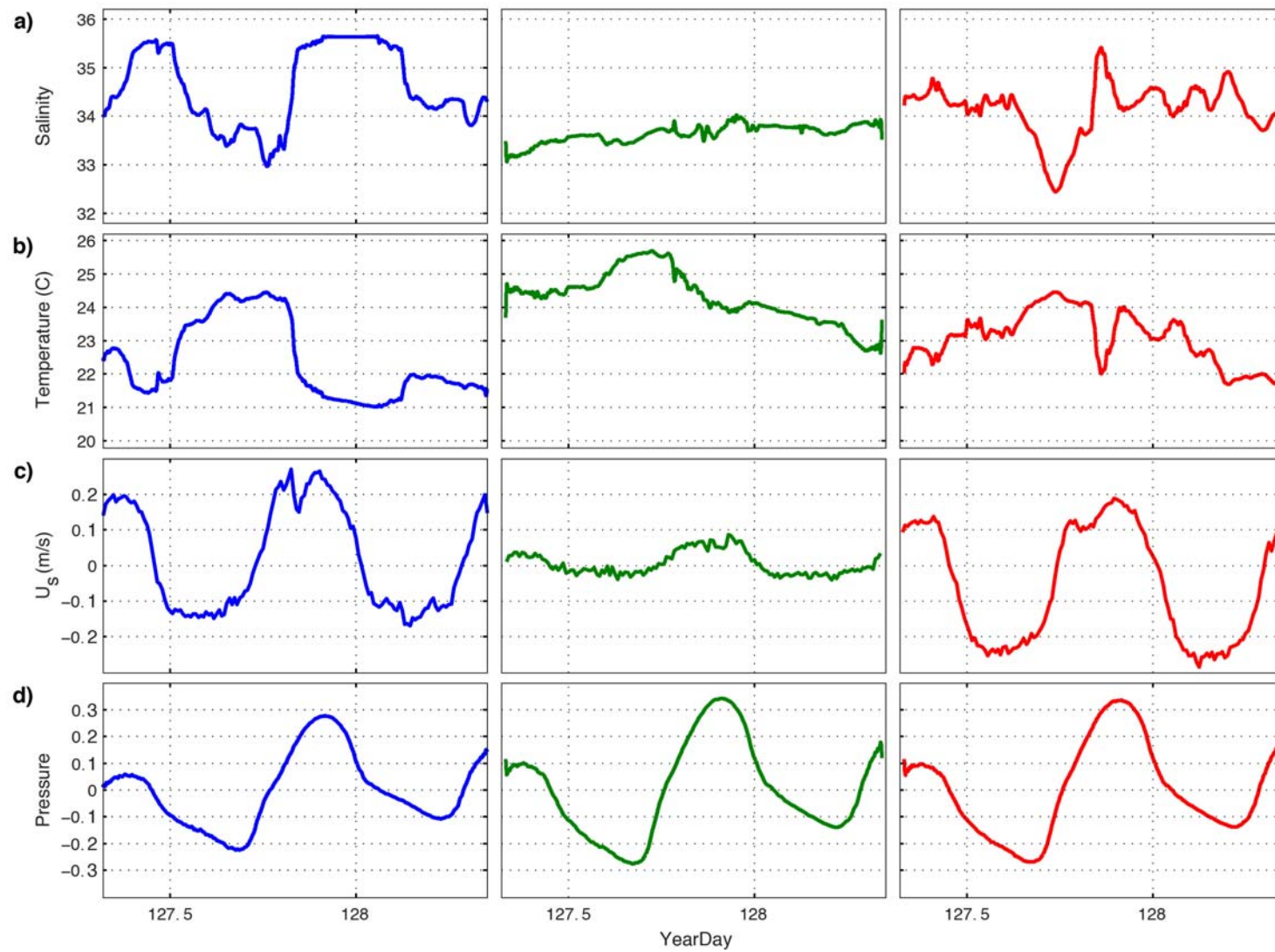


Figure 8. Minicat data from side bays, from left to right are stations C1, C2, and C3.

### **C. MINI CATAMARANS-ICWN**

The ICWN is examined using minicats from yd125, which are spread out from the entrance of the ICWN, to the northward bend and from a minicat anchored north of the bend on yd131 (Figure 9). Tidal variability is similar in all locations and fluctuates by  $\pm 0.4\text{m}$ . Temperature and salinity vary with locations and the tidal cycle, but generally range from 33–35.7 psu and from 21–25.7 °C. The pressure sensors do not a significant decrease in amplitude,  $\sim 3\text{ cm}$ . With the exception of station C4 on yd125, the streamwise velocity is in-phase with pressure head; flood tide is associated with positive (inland) velocity. For minicat C4, the streamwise velocity is out-of-phase with pressure head; flood tide is associated with negative (northern) velocity. The relationship between temperature and salinity is similar to that of the main channel where higher salinities are tied to lower temperatures and vice versa.

As the flood starts on yd125, slack water at station C4 increases to a northerly flow, salinity reaches a maximum of 35.5psu and temperature decreased to a low of  $\sim 21.5^\circ\text{C}$ . At the peak of flood tide, the flow switches southerly, salinity drops 1psu and temperature increases  $\sim 3^\circ\text{C}$ . This salinity drop is followed by a second peak, up to 35.3psu and a drop in temperature to  $23.5^\circ\text{C}$ . The flow at stations C5 and C6 follow a different pattern. During the same period, the flood starts with positive (inland) flow, salinity decreases to a minimum of  $\sim 33.8\text{psu}$ , and temperature reaches a maximum of  $\sim 25^\circ\text{C}$ . As the flood reaches its peak, salinity increases and temperature decreases. By the time the tide turns, salinity has reached a maximum of 35.5psu and a temperature minimum of  $23.5^\circ\text{C}$ . The flow patterns of yd131 follow those of the main channel, streamwise flow and pressure head are in-phase, flood tide is associated with positive southerly flow. Incoming flood results in increasing salinity and decreasing temperature. Variation in salinity is present during the ebb tide of yd131.

### **D. MINI CATAMARANS-ICWS**

The ICWS was analyzed using minicats from yd125, stationed from the mouth of the ICWS to the southward bend and from a minicat stationed south of the bend on yd131 (Figure 10). In general, the ICWS has a tidal variability of  $\pm 0.27\text{m}$  and a salinity and

temperature range of 34–36.8psu and 21–26.5 °C, respectively. The pressure timeseries shows a wave that becomes nonlinear as it travels further into the ICWS. The pressure and the streamwise velocity are in-phase; floodtide represents either an offshore (yd125) or a southerly (yd131) flow. Unlike the main channel or the ICWN, there is a time-lag between the velocity and pressure head. At station C2 yd125 for example, maximum southerly flow occurs ~1.75 hours before maximum pressure head is reached; the flow switches to a northerly direction ~1 hour before pressure head becomes negative. Other stations in the ICWS exhibit a similar pattern, with the lag-time increasing further south the ICWS. At Station C2 yd131 for example, maximum velocity is reached ~3.65 hours before maximum pressure head and the velocity switches direction ~4.37 hours before pressure head becomes negative. The ICWS also differs from the ICWN and the main channel in that the temperature/salinity relationship is not consistent.

During ebb tide on yearday 125, station C2 has a salinity concentration of ~36psu, while station C1 has ~36.8psu. As the flood starts to come in, salinity at station C2 drops by approximately 2psu; 1.7 hours later, salinity at station C1 drops to ~35psu. This salinity drop is followed by a sharp increase, such that by maximum flood, all stations plateau at 35.8psu. Temperature follows a similar pattern; during ebb tide temperature at station C2 is ~25°C and ~26°C at station C1. As the tide starts to come in, temperatures increase slightly before decreasing, reaching a minimum during maximum flood when station C2 lowers to ~21°C and station C1 to ~23.5°C. Yearday 131 shares the same general temperature/salinity patterns as yearday 125.

The ebb tide of yearday 131 is associated with high salinity (~35.5psu) and high temperatures (25.5°C). Although the incoming tide causes no changes in salinity and temperature, during maximum southerly flow, temperatures start decreasing and salinity suddenly drops to ~34psu. The salinity then increases to 35psu, and at the same time temperature reaches a low of 22.3°C. As the flow becomes northerly, the temperature starts to increase while salinity decreases once again, reaching 34.7psu at max ebb. From this point forward, the salinity and temperature start to increase.

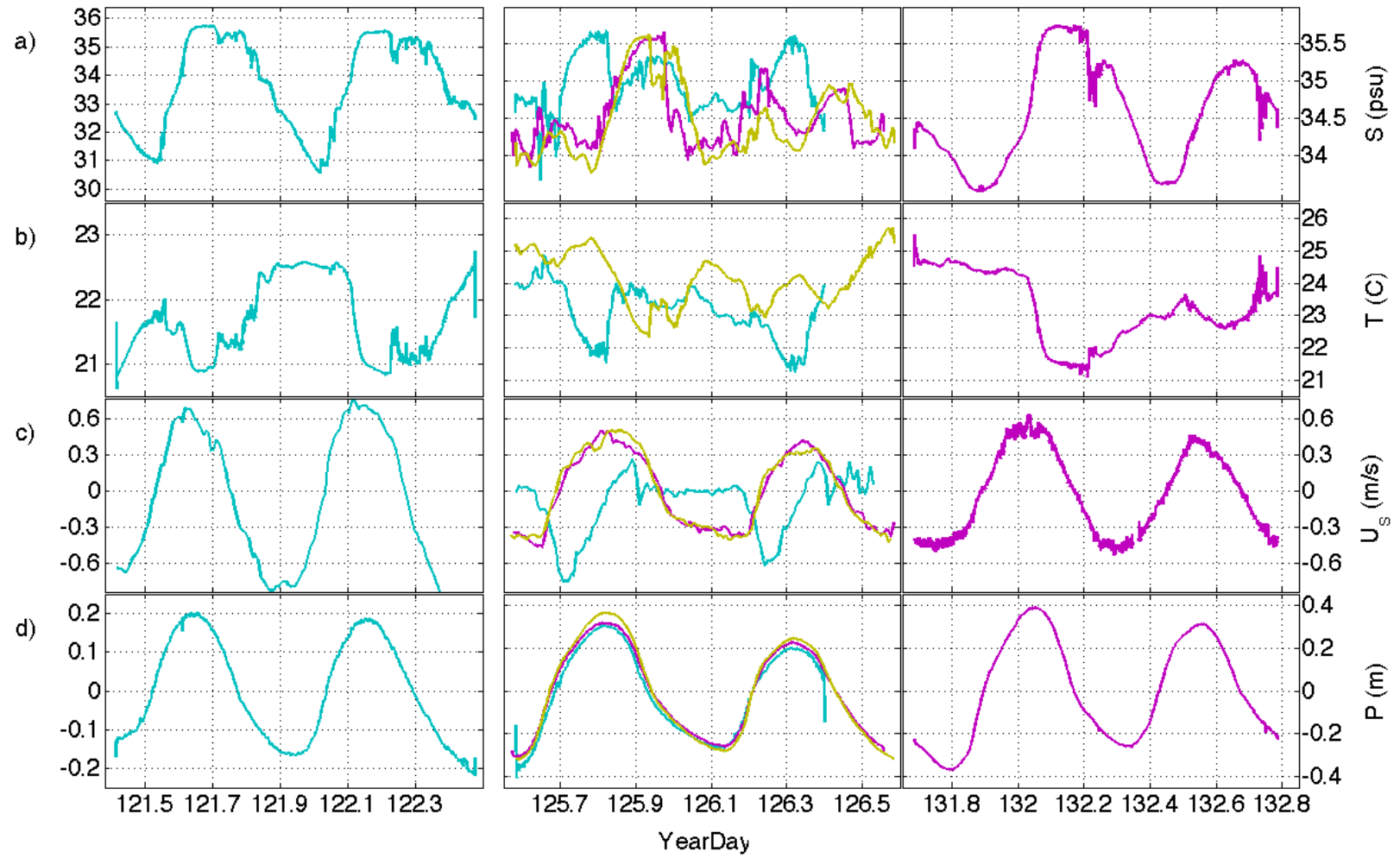


Figure 9. Mini catamaran data from the main channel (yd121) and the ICWN (yd125 and 131), **a)** salinity, **b)** temperature, **c)** streamwise velocity, and **d)** demeaned pressure. Yeardays 125, and 131 have a common y-axis. For each yearday, the color represents the catamaran identifier from Figure 3: C4=cyan, C5=magenta, C6=gold.



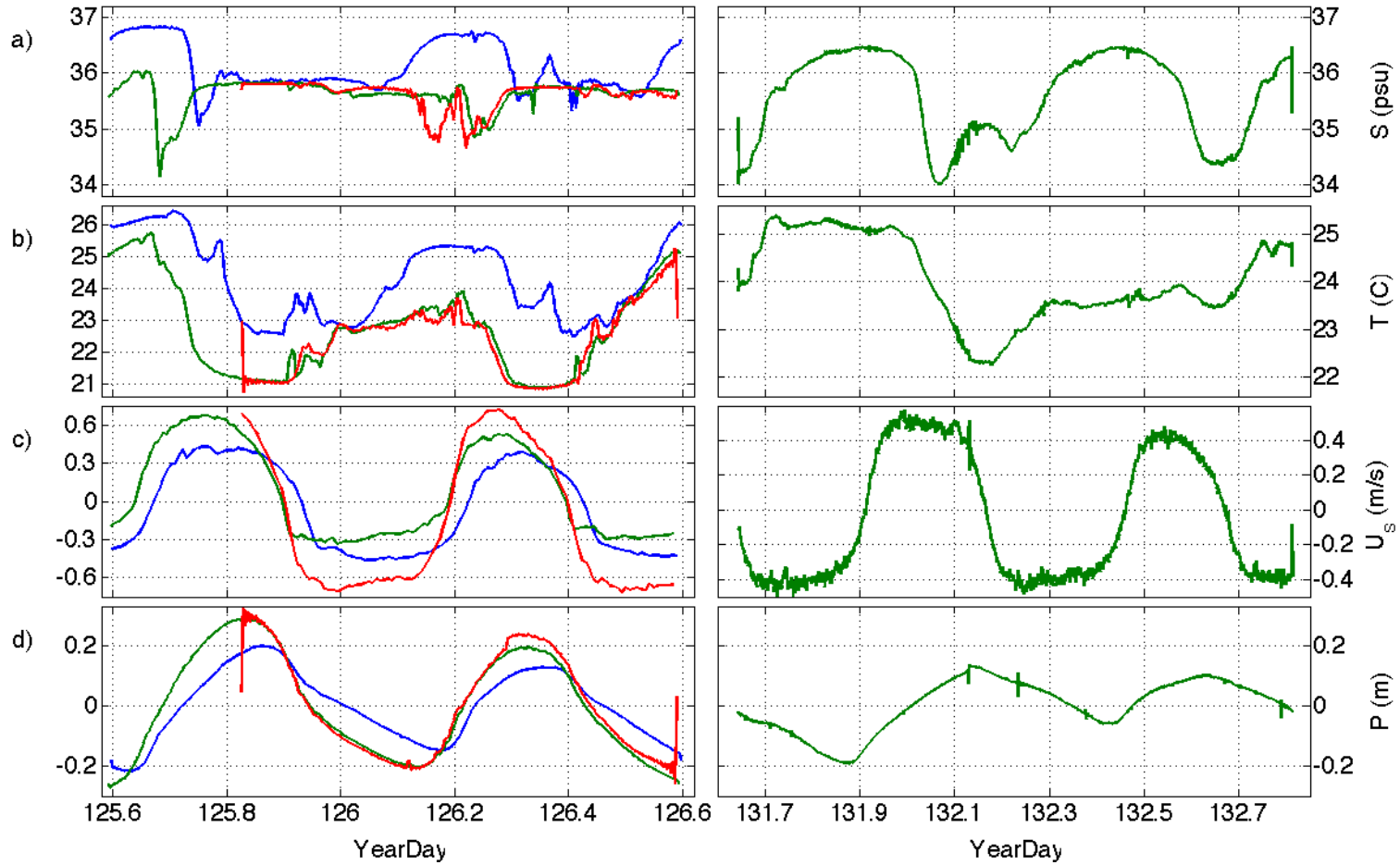


Figure 10. Mini catamaran data from the ICWS, **a)** salinity, **b)** temperature, **c)** streamwise velocity, and **d)** demeaned pressure. For each yearday, the color represents the catamaran identifier from Figure 3: C1=blue, C2=green, C3=red

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## **IV. DISCUSSION**

### **A. WATER MASS IDENTIFICATION**

There are three unique water masses and one varying mixed water mass in the New River estuary (Figure 6a). The ocean water outside of the inlet consists of low CDOM, high salinity, and low water temperatures. The backbay water contains high CDOM, low salinity, and warm temperatures. Similar to the backbay, the southern ICW contains high CDOM and warm temperatures, but its waters are hyper-saline (~37psu). The mixed water mass is composed of a wide range of CDOM, salinity, and temperature by the three water masses. It is distributed from the mixing area of the ICWS, through the ICW intersection, to the ICWN.

The addition of CDOM to the traditional temperature and salinity diagram provides more detailed information on water masses. While the three unique water masses can be identified using a TS diagram (Figure 6b), CDOM provides more insight into the mixing and dilution processes. The TS diagram shows water in the ICWS with similar characteristics to that found in the main channel. The high CDOM concentration (Figure 6a) identifies it as the ICWS water mass that has mixed, decreased in salinity and temperature, and in some cases, diluted the CDOM. The more conservative nature of CDOM aids in analyzing how the unique water masses mix in the different regions.

### **B. WATER CIRCULATION**

The general circulation of the New River estuary, in which ocean water flows into the main channel during flood tide and backbay water exits during the ebb tide, is modified by the ICW and the dredge spoils. Ocean water enters the main channel, flows past the ICW intersection and does not continue much farther past the spoils, as evidenced by the short duration of the salinity plateau at C3 yd121 (Figure 7a). Tidal intrusion fronts form in this area, where the backbay opens back up (M. Weltmer, personal communication). This suggests that the dredge spoils extend the main channel into the backbay, allowing ocean water to travel farther inland. The salinity, temperature and CDOM gradients shown Figure 5 are possible because the dredge spoils extend the

main channel. During the ebb, the brackish water from the backbay flows toward the inlet opening. The front dissipates during the ebb, creating a wavelike disturbance in its wake. The wavelike disturbance creates pockets of water with different physical characteristics, causing the salinity and temperature ebb variation detected in downstream main-channel sensors (Figure 7a and 7b). The ebb variation is extreme in the backbay (Figure 7a, C1–C3, yd121) at the boundary of the intrusion front. The variation decreases as the pockets of water mix and travel toward the inlet opening (Figure 7a, C4–C6, yd121).

Dredge spoils act as small levees limiting the exchange between the main channel and side bays. The side bay in which station C1 was anchored is located outside the influence of dredge spoils and behaves similarly to the main channel (Figure 9). The dredge spoils north of the main channel influenced circulation such that station C3 has limited exchange with the main channel and station C2 in Traps Bay has near constant salinity.

The ICWN is affected by contrasting water flow between the main channel and Browns Inlet (Figure 8). As ocean water floods into the backbay through the main channel, some enters the ICWN. Ocean water flooding Browns Inlet drives the warm, low saline water of the ICWN southward, impeding the main-channel ocean water from entering. Ocean water from Browns Inlet finally reaches the opening of the ICWN near the turn of the tide, inducing a second salinity peak in station C4 (yd125). The water pockets formed during ebb tide exit the backbay through the ICWN in addition to the main channel.

Limited water exchange in the ICWS leads to its extreme characteristics. Ocean water enters the ICWS after flooding the main channel. This drives the warmer and often lower-saline water from the ICW intersection into the ICWS, causing an initial drop in salinity. Some of this water spills into Chadwick Bay and some continues south past the bend to station C2 (yd131). Cold ocean water follows closely behind, reaching Chadwick Bay during max flood. Station C2 (yd131) represents the extent of ocean-water penetration into the ICWS, and during ebb tide, water returning past this point is more saline. The reverse flow, however, does not force the hypersaline water past Chadwick

Bay. Cast data from the Chadwick Bay area indicate that it is a source of CDOM and produces the variability seen in this section of the ICWS.

The proximity effect of adjoining inlets on the circulation of the intra-coastal waterway is evident in the data. Browns Inlet's close proximity allows the pressure wave in the ICWN to remain sinusoidal with minimum amplitude loss,  $\pm 0.4\text{m}$  at the inlet opening versus  $\pm 0.38\text{m}$  in the ICWN. On the contrary, the distance between Topsail Inlet and New River Inlet results in a nonlinear pressure wave and a tidally choked ICWS; the pressure head amplitude range is half of the inlet opening,  $\pm 0.2\text{m}$ . These two neighboring inlets also affect the water characteristics. The ICWN has increased exchange between the backbay and the ocean, the ICWS does not, resulting in high concentrations of CDOM and salinity. In summary, unimpeded flow exists between the backbay and main channel, while circulation in the ICW is affected by neighboring inlets.

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